EULERIAN-BASED WALL SHEAR STRESS TOPOLOGICAL SKELETON AS A TEMPLATE OF NEAR-WALL MASS TRANSPORT IN ARTERIES

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Introduction

Several studies have suggested that mass transfer and transport (e.g., of high plasma levels of low-density lipoproteins, LDL) are involved in the atherosclerosis process [1]. In the last decade, computational fluid dynamics has been largely adopted to elucidate how flow disturbances, mass transport and atherogenesis are linked in human arteries [2]. However, modelling mass transfer in cardiovascular flows requires high computational costs [3]. To overcome this limitation, a marked interest has recently emerged on the Lagrangian-based features of the wall shear stress (WSS) topological skeleton (TS), able to provide a template for near-wall transport [4]. Briefly, the WSS TS is composed by fixed points, points where WSS vanishes, and stable/unstable manifolds, identifying WSS expansion/contraction regions. Here, a recently proposed Eulerian-based method for WSS TS analysis [5] is used to provide a reliable template of near-wall mass transport in patient-specific computational hemodynamic models of three distinct vascular regions. The capability of the proposed approach to depict an affordable picture of the near-wall mass transport is tested against LDL polarization distributions simulated solving the coupled Navier-Stokes (NS) and advection-diffusion (AD) equations.

Methods

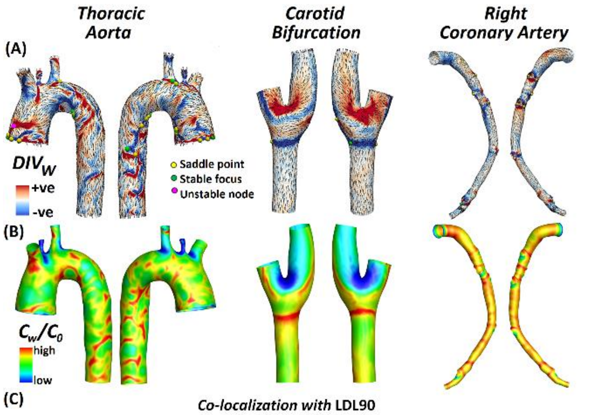
The 3D geometries of a human thoracic aorta, a carotid bifurcation, and a right coronary artery were reconstructed from medical images. The finite volume method was applied to solve the coupled NS and AD equations on high-quality mesh-grids [3]. Subject-specific flow measurements were prescribed as boundary conditions. LDL boundary conditions, in particular blood-to-wall transfer were modelled as proposed elsewhere [3]. A recently proposed Eulerian-based WSS TS analysis [5] was here considered. Based on theory and according to [5], the divergence of the WSS unit vector field $\boldsymbol{\tau}_u$, defined as:

$$DIV_W = \nabla \cdot \left(\frac{\boldsymbol{\tau}}{\|\boldsymbol{\tau}\|_2}\right) = \nabla \cdot \boldsymbol{\tau}_u \qquad (1)$$

represents a template of the WSS vector field manifolds, identifying WSS expansion/contraction regions. The Poincarè index and the Jacobian analysis were then used to identify and classify fixed points [5]. In addition, the canonical descriptors of flow disturbances, i.e., *TAWSS*, *OSI*, and *RRT*, were evaluated. The surface areas (SAs) exposed to high local LDL uptake (LDL90), WSS contraction regions (DIV10), and disturbed hemodynamics (TAWSS10, OSI90, RRT90) were identified, and their co-localization was quantified [3].

Results

DIV_W and LDL luminal distributions are provided in Fig. 1. WSS contraction/expansion regions are coloured in blue/red (negative/positive DIV_W, Fig. 1A). A marked co-occurrence of WSS contraction regions and LDL concentration polarization on the vessels wall clearly emerges. These observations are confirmed by quantitative analysis (Fig. 1C), reporting that WSS contraction regions co-localize with high LDL concentration regions at least the 40% more than canonical WSS-based descriptors.



(C) Co-localization with LDL90

	TAWSS10	OSI90	RRT90	DIV10
Thoracic Aorta	33%	27%	34%	46%
Carotid Bifurcation	30%	28%	29%	48%
Right Coronary Artery	21%	19%	20%	35%

Figure 1: A) Cycle-average WSS TS. B) LDL wall concentration. C) SAs co-localization.

Discussion

Our findings clearly indicate that the Eulerian-based method for analysing the WSS TS [5] provides an effective template of WSS manifolds, which in turn co-localize with LDL polarization areas at the luminal surface. This means that the DIV10-based approach: (1) identifies high LDL polarization areas at the luminal surface better than canonical WSS-based descriptors; (2) reduces computational costs and methodological complexity with respect to classical mass transport simulations.

References

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